



A BIM-Based Model for Heritage Conservation and Structural Diagnostics: The City Walls of Pisa

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Abstract. The use of Historical Building Information Modeling (HBIM) is gaining much interest in the architectural heritage domain due to its ability to support the design and management of conservation activities. Any maintenance, preservation or revitalization strategy requires obtaining a complete knowledge of the site and conducting critical investigations on geometrical, physical, and documental data. The benefits of implementing HBIM comprise the possibility to integrate the data coming from multiple sources, inspections and diagnosis techniques, as well as to employ standardized and robust tools for orienting cultural heritage asset management. This study explores the challenges of developing HBIM on ancient city walls, whose great dimension and extension require adapting the conventional workflow in order to obtain results in a reasonable time. The combination of traditional geometric surveys and more innovative techniques allows for a complete and extensive photogrammetric documentation of the city walls. The acquisition process has been speeded up without compromising the accuracy of the resulting model, thus offering a reliable representation of multiple issues of the historical assets, ranging from its features and state of conservation to its structural deficiencies. By applying the novel workflow to the city walls of Pisa, the paper discusses the interoperability among different tools and the broad versatility of the proposal for large architectural heritage.

Keywords: HBIM · City walls · Cultural heritage · Preventive conservation

1 Introduction

Planned preventive conservation entails the protection of cultural heritage and is founded on the attentive identification of situations of risk and the systematic

planning of minimally invasive interventions [1]. This approach ensures greater efficiency in terms of costs and results with respect to unplanned systems based only on corrective actions [2], which may not be able to remove the causal factors of disasters. Conversely, planned preventive conservation is a proactive management process to avoid unnecessary deterioration, damage and even failure by means of periodical monitoring, scheduled maintenance and integral condition assessment. A specific challenge in this field is to develop easy methods to establish a virtuous management process for large architectural heritage assets, such as ancient city walls, which require great effort to accurately document and represent the current state of conservation as well as to handle interventions avoiding economic burden.

City walls played a key role in defending people and places from foreign invaders and have been significant for shaping local identities since the remotest period. Today, they hold great potential as cultural resources, as they are large preserved iconic attributes of civic pride and identity. However, the effective implementation of the planned preventive conservation of such a large number of monumental constructions spread across a vast territory is a challenging task and is still under-researched. Many failure events have recently occurred in diverse sites and countries [3, 4] stressing the need to ensure systematic, condition and significance-based conservation, repair and maintenance of historical structures.

The conception and implementation of novel tools for managing the conservation process of city walls may increase the operative capacity by fostering the transfer and sharing of data between different professionals, from archaeologists to engineers, and governmental actors, from regional to local ones. Significant contribution may derive from the application of Heritage Asset Management (HAM) principles, which promote a multi-disciplinary, knowledge-based decision making driven by comprehensive and up-to-date data, with explicit leadership and responsibilities [5]. However, there is still no standard procedure or framework for HAM, even though some advancement are being experimented by applying Building Information Modeling (BIM) [6]. In the case of historical buildings, the literature refers to Heritage BIM (HBIM) [7] as an effective approach to pursue the modelling of architectural elements and to handle a great amount of data coming from multiple sources. The benefits of HBIM are manifold, ranging from the documentation of the current state to the assessment and monitoring of intervention.

The case study presented in this paper concerns a large sector of the city walls of Pisa, a well-preserved fortified system located in Tuscany (Italy). The walls are a remarkable example of the Medieval construction techniques and present peculiar characteristics, with slender curtain walls, high-rise towers, wide gates, and bastions. The creation of a decision support system for the city walls is based on the multidisciplinary and cross-scalar knowledge of the assets that are investigated by applying a HBIM methodology. As such, this contribution gives special emphasis to the survey and modelling phases by experimenting a novel scan-to-BIM approach. The proposed workflow is capable of ensuring a rapid,

yet accurate and reliable, result by speeding up the data acquisition and the 3D model creation and information.

2 Related Works

In the last decades, the research progress in the field of 2D and 3D digital data allowed scholars and heritage experts to rely on accurate models to document the consistency and conservation state of cultural assets. With respect to 2D media, 3D models have the great advantage of providing a comprehensive and metrically correct representation of the building geometry. They can be obtained by using solid modelling techniques, which can be directly or parametrically handled by the user according to the time and precision of the expected results, or by direct triangulation of point-cloud data, which instead are influenced by the quality of the point-cloud itself.

By and large, multiple techniques have been developed for range-based (e.g., laser scanner) and image-based (e.g., photogrammetry) reconstructions of architectural objects, and the selection of the most suitable approach is usually conducted on a case by case criterion. Indeed, diverse modelling techniques are usually employed in parallel because none of them is individually able to ensure high geometric accuracy, portability, full automation, photo-realism and low cost at once, together with flexibility and efficiency in the surveys [8].

Once 3D models are created, several pieces and types of information can be registered on it, thus creating enriched or *ontological* models [9]. This task entails a preliminary documentation of the heritage assets and a retrospective analysis of several sources. Data rich 3D models can be included in interfaces and platforms that also collect reports, analog/digital pictures, drawings, and archival documents [10], thus producing digital libraries to organize, access and manage content. Several studies have also added a temporal dimension (diachronic and synchronic) to the 3D architectural model [11, 12] in order to describe the evolution of the building during its life cycle. Few studies explored how the use of 3D models and web-based digital platforms can support restoration activities [13], also documenting the project operations and advancements.

Meanwhile, BIM has become popular in the civil engineering sector thanks to its ability to produce and manage structured digital information and multidisciplinary design skills. The process is supported by several software tools - continuously improved for reaching higher quality, lower errors and cost reduction - that ensure a coordinated, consistent and always up-to-date working model. In the architectural heritage domain, the advent of advanced surveying techniques is leading to the development of reality-based HBIM methodologies, that rely on as-built/as-is models. The models depict the actual state of the building and can be semantically enriched with a wide range of data.

Despite these advances, critical aspects include the elaboration of data from different sources, such as material properties, historical stratifications, and damage patterns, which may inform conservation practices more effectively if coupled with 3D representations. Currently, several BIM platforms have are being used

by experts to perform the modelling, visualization, compilation, and management of the knowledge of architectural heritage. However, the interoperability among the available tools within a scan-to-BIM process and the lack of historical parametric object libraries are still debated topics.

3 The City Walls of Pisa

The city walls of Pisa were built in Medieval times, starting from the XII century, to defend the central settlement of the historical Maritime Republic. The process of extension and consolidation of the domain over the territory, as well as the continuous conflicts with nearby cities, led to the design and construction of advanced defensive systems that are considered as monuments of inventive genius and skill. Although they have progressively lost the protective function, the walls have been preserved and only limited sectors of the perimeter have been lost over the centuries.

Today, the overall length of the circuit is approximately 7 km, the average height of the curtain walls is 11 m, and the thickness is about 2 m. The structure is made of multi-leaf masonry, with two stone outer-leaves with localized brick portions and the inner core of irregular masonry. It is built using local techniques, workmanship, and materials, particularly the sedimentary stone “Brecchia” from Asciano, the Limestone from San Giuliano, or a yellowish calcarenite from Livorno (classified as “Panchina” Fm. Calcarenite) [16, 17].

The circuit of the city walls has been classified according to the morphological type of element, thus distinguishing the curtain walls, gates, towers, bastions, and fortresses. Each element has been identified with an alphanumeric code that refers to the typology associated with a sequential numbering. A summary of the adopted classification is in Table 1. As shown in Fig. 1, the sectors investigated in this study correspond to: the curtains labelled as CUR.01, CUR.02, CUR.03, CUR.04, and CUR.05; the gates coded as GATE.01, GATE.02 and GATE.03 (i.e., Porta Nuova, Porta del Leone, and Porta Santa Maria, respectively), and the towers labelled as TOW.01, TOW.02 and TOW.03 (i.e., Torre del Catallo, Torre del Leone, and Torre Santa Maria, respectively).

Table 1. Codification system for the city walls of Pisa

Element type	Curtain wall	Gate	Tower	Bastion	Fortress
Code	CUR	GATE	TOW	BAS	FOR
Numbering	1–49	1–15	1–11	1–3	1



Fig. 1. City walls of Pisa. At the top, general view and classification of the walls; at the bottom, two emblematic sectors of the walled system.

3.1 Data Acquisition

The geometrical survey is conducted through photogrammetric techniques combined with topographic measurements to derive the 3D coordinates of several targets and control points onto the architectural heritage.

The application of Structure from Motion (SfM) photogrammetry allows for reconstructing the 3D geometry of the scene starting from a rapid and less demanding data acquisition phase. This method is able to automatically and iteratively solve the positioning and orientation of cameras from a set of many overlapping images, without the need to provide a priori a network of targets.

Redundancy is a key requirement in the acquisition phase [14], therefore photographs shall be taken from a wide array of positions and in uniform lighting conditions. In the case of city walls, some issues may arise in practice owing to the limited accessibility and the great dimension of the object, which

force the surveyor to rely on long-distance shootings. The great distance between the camera and the feature of interest decreases the spatial resolution of the photographs, which in turn produces low-density point clouds.

Positional data (x, y, z) are used as control points to scale the 3D reconstruction of the scene to an absolute coordinate system, as well as to manually adjust any misaligned camera. Coordinates can be collected with several range-based methods, such as a laser scanners or more traditional surveying instruments. In this study, the survey employed a Total Station that provides high-quality and precise coordinates of a series of control points. Besides, the survey exploits remote technologies like Global Positioning Systems (GPS) in the shooting of photographs in order to improve the alignment and orientation of cameras. The result is a scaled point cloud of the investigated sector of the city walls (Fig. 2), which is later used to create the 3D model. It is interesting to note that these control points are also used in the processing phase (see Sect. 3.2) to set the projection planes of orthomosaics and annotation maps.

Photographs were acquired using an iPhone 11 camera having a resolution of 12MP and a 1/2.55-in. sensor, with GPS on. The distance from the wall ranged between 7 m and 12 m depending on the accessibility, which was often limited due to presence of trees, roadways, and fences. Photographs were taken in longitudinal strips ensuring a high degree of overlap (about the 70% on average), with two bottom-to-top shots wherever the shooting distance was too small to acquire the whole wall height. Additional photos of the walls have been taken from the wall walk to capture the upper parts with a sufficiently good resolution. The acquisition was done over several days at different times, to have the most uniform illumination possible, avoiding too-strong direct light and hard shadows.

Photographs and positional data have been processed using the SfM software Agisoft Metashape [15]. The dense cloud of the investigated sector of the city walls is obtained from an overall number of photographs equal to 348 over a total length of approximately 400 m.

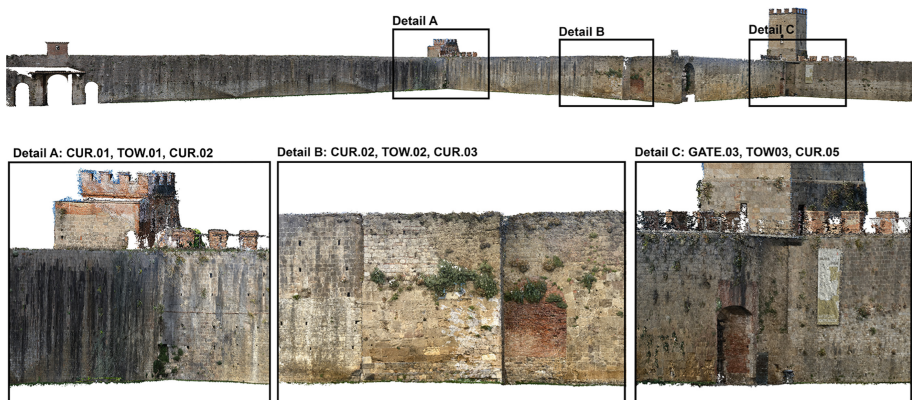


Fig. 2. Perspective view and details of the city walls of Pisa processed with SfM photogrammetry.

3.2 Data Processing and 3D Modelling

The 3D architectural model has been generated starting from the dense point cloud, after a process of refinement that entails filtering out areas with poor confidence and reducing noise generated by any reprojection error.

The model derives from the automatic triangulation of the dense point cloud in Agisoft Metashape, which produces a 3D textured mesh of the investigated sectors (Fig. 1). Figure 3 shows the 3D reconstruction process of a portion of the walls, comparing the rectified real photographs (a) with the dense point cloud (b), the model in solid visualization (c), and the tiled textured model (d). The mesh and the texture preserve a good level of detail, compatible with the large dimension of the object under investigation, as they are able to reproduce the geometric irregularities of the city walls.

The model has been used to generate 7 orthomosaics, namely high resolution imagery obtained from the projection of the reconstructed object over a reference surface, which can be used as a basis for the diagnosis and the annotation of wall properties. Given the approximately planar geometry of city walls, the projection surface is a plane that has been defined by assigning three Marker-Points in Agisoft Metashape.

The model can be exported in three-dimensional format (e.g., obj wavefront, fbx, 3ds, ...) that guarantees the direct association of the processed texture even in a different software. In this study, the final tiled model textured has been imported in the McNeel Rhinoceros software [18] that is able to easily manage complex geometries and hosts Grasshopper, an algorithmic modeling environment supporting a wide range of useful plug-ins. The scan-to-BIM procedure herein proposed employs the Grasshopper plug-in *Archicad Live Connection* developed by Graphisoft, which enables the connection with the Graphisoft Archicad software [19]. Specifically, the Grasshopper-Archicad Live Connection makes it simple to generate native Archicad BIM elements in Grasshopper using familiar nodes, automating and simplifying common and complex processes.

Once the model of the city wall sectors has been imported in Rhinoceros as a continuous textured mesh, the geometry has been cut to clearly distinguish the elements according to the proposed classification system (Table 1). Further operations have been performed to aid the information of the model with data that are typically annotated on 2D media and orthoimages, such as deterioration patterns (e.g., decay, degradation, damage) and materials [3, 16]. All these pieces of information have been included into an “annotation plane” (Fig. 4), which can be correctly positioned in the 3D space using the same Marker-Points previously defined in Agisoft Metashape for generating the orthomosaic. Each annotation plane contains closed 2D entities that lie on that plane and that identify and delimit the different features of the architectural heritage under investigation.

At the same time it is important to prepare a file on Graphisoft Archicad that will host the three-dimensional entities and its customized set of BIM features, through the creation of specific properties regarding historical, material, structural and morphological data. This set of features will constitute the semantic structure for the final HBIM model.

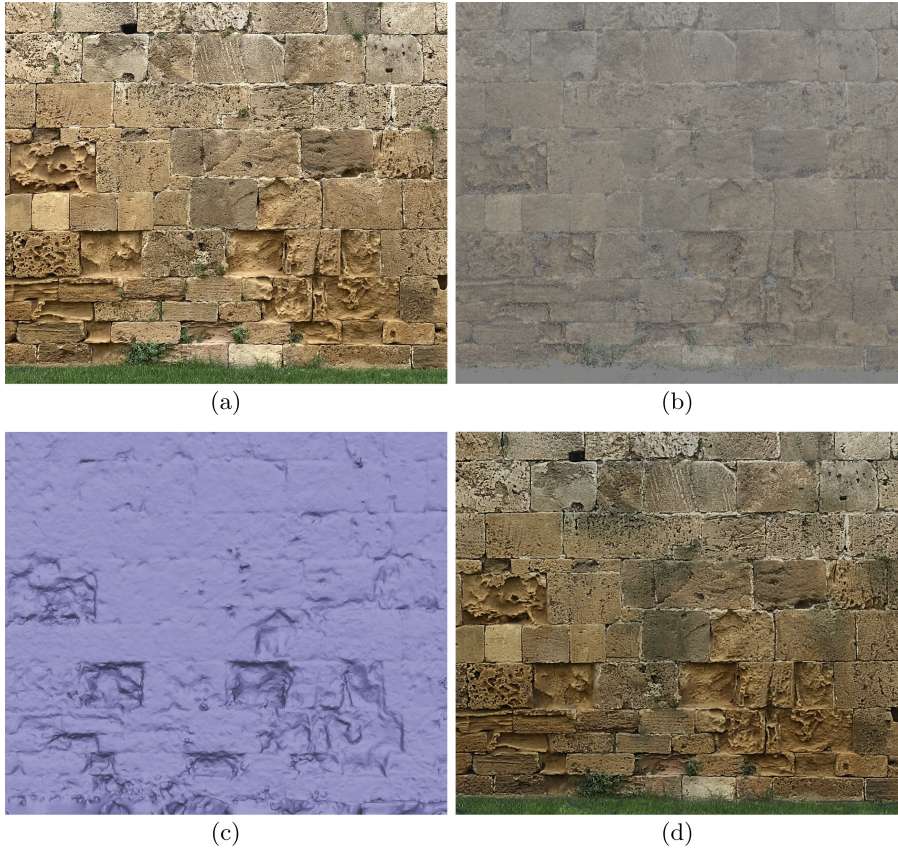


Fig. 3. 3D reconstruction process and level of detail on a portion of the CUR.04: (a) rectified real photograph; (b) dense point cloud; (c) model in solid visualization; (d) tiled model textured.

3.3 Model Information

The main advantage of HBIM lies in the possibility to integrate into a single model multiple type of data from diverse documentary sources, inspections and diagnosis techniques. In fact, the survey is not limited to the geometry of the city walls, but also concerns the building technology and its deterioration patterns. Site inspections can supplement historical and archive research, thus providing direct critical knowledge to experts.

The diverse materials and deterioration patterns are singled out and annotated on 2D representations of the asset, by drawing the polygons or regions over the representation itself. Typically, this operation is time-consuming since it consists in the manual drawing of the areas, however recent research efforts explored the use of human-centred AI-powered tools for the semantic segmentation of 2D orthographic images thanks to the software TagLab developed by

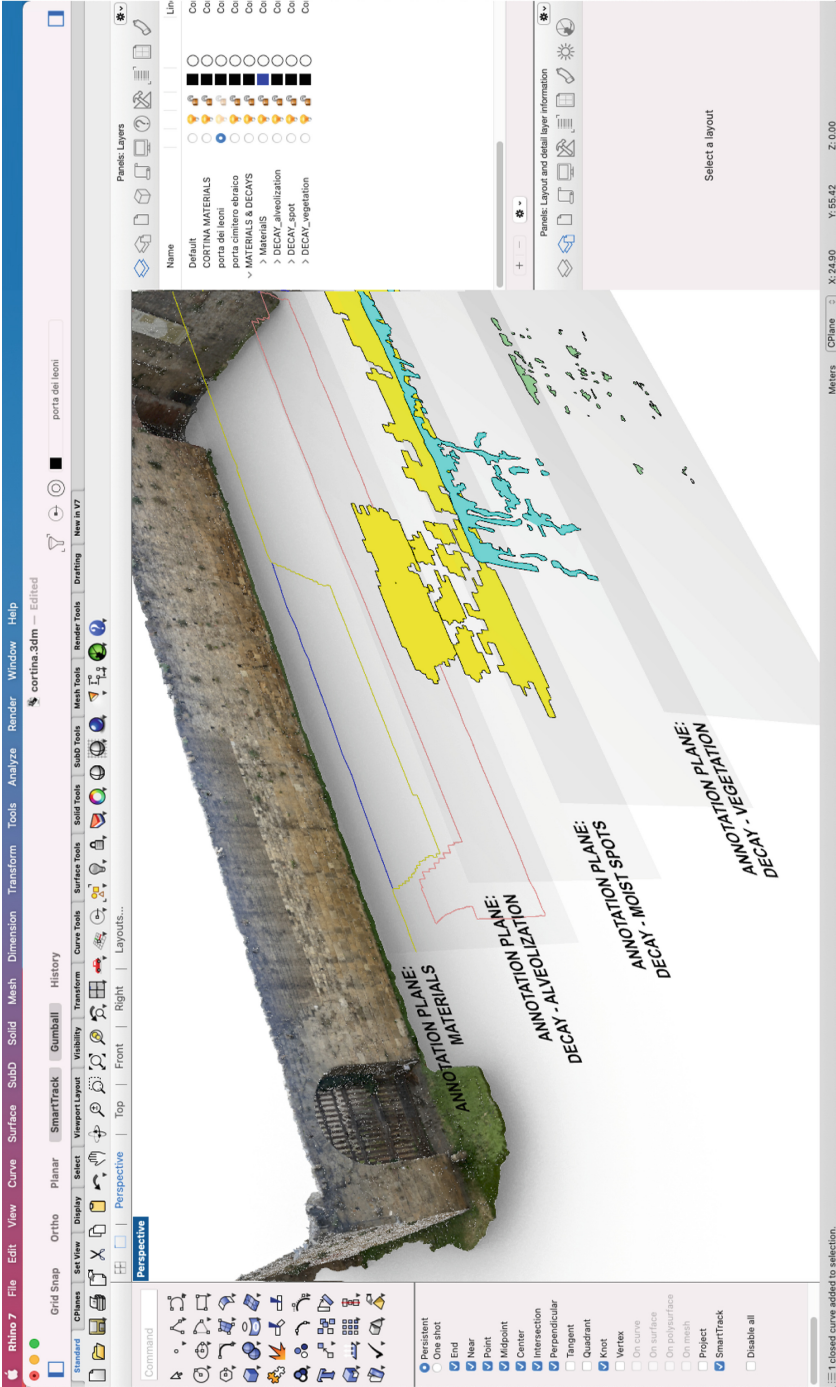


Fig. 4. Annotation planes for the curtain wall CUR.04

the Visual Computing Lab [20]. As for the city walls of Pisa, the orthomosaics have been generated on Agisoft Metashape and later annotated by using this novel software that can significantly reduce the processing time and optimize the semantic segmentation [16].

As previously anticipated, the semantic structure of the HBIM has been set up in Archicad and finalized through the use of the *Options/Property Manager*, which allows for creating new specific properties that will be punctually associated to the 3D model. In this case study, the set of *New Properties* and *New Group Properties* has been defined as in Table 2.

Table 2. Customized groups and properties set for the HBIM of the city walls of Pisa.

New group property	New properties
HBIM identity data	Image; Comments; Tag; Element code; Periodization of historical transformations; Historical documentation; Documentation of the current state; Stratigraphic analysis; Masonry typology; Wall type; Intervention; Period of intervention; Maintenance plan; Criticality of the context or asset
HBIM design parameters related to masonry types	Representation; Block - composition; Block - surface processing; Block - representative size (hxbxt); Block - shape; Block - color; Joints - mortar composition; Joints - morphology and surface finish; Joints - color; Joints - horizontal thickness representative value (t); Joints - vertical thickness representative value (t); Texture - recourses; Texture - joints offset; Plaster; Section - core composition; Section - core type; Section - connection between core and block; Section - Total thickness

3.4 Connection Between the 3D Model and the Information

The mesh model imported in McNeel Rhinoceros is “splitted” with the Grasshopper *Mesh Split* component using the closed 2D entities previously defined in the annotation plane, referring to materials or decays (Fig. 4). This operation will produce new sub-meshes associated with different properties. These meshes are connected to the Grasshopper-Archicad Live Connection component *Morph-solid* (in this case study the morph entity was chosen), in which it is possible to connect relative *Morph Settings*. Such settings are also referred to Archicad software settings and can therefore be defined in the Grasshopper environment. Among these settings, it is possible to load all the new customized properties of the “HBIM identity data” and of the “HBIM-Design parameters related to masonry types” (Table 2), which were defined in the Archicad file, and thus proceed with the assignment and compilation of the information related to the elements of the architectural heritage, directly in the Grasshopper environment (Fig. 5).

At the end of this procedure, the *Synchronize* tool in Grasshopper will import the mesh and all the related HBIM information in the Archicad file. In Archicad environment it is possible to manage the information related to the historical artifact through the setting of *Graphic Override Combinations* to which *Graphic Override Rules* are associated. The latter links typed graphic views according to the assigned information (Fig. 6).

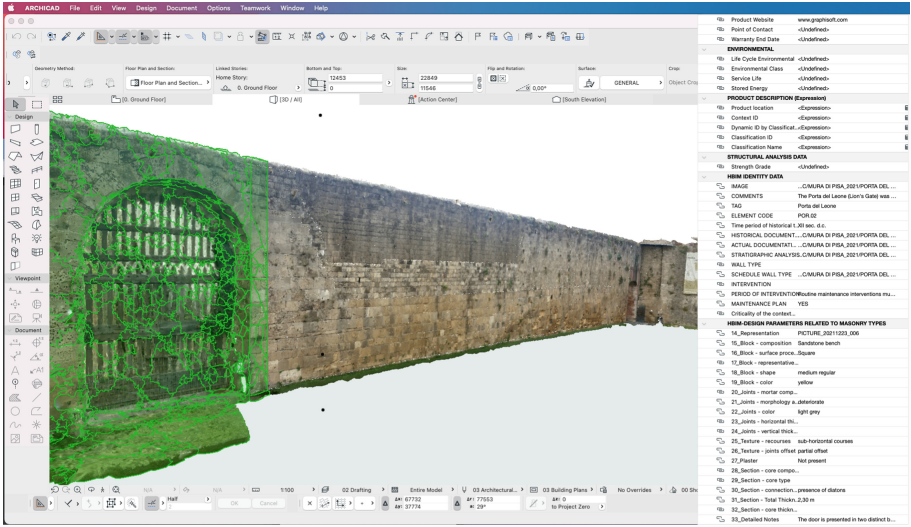


Fig. 5. HBIM in Archicad. The selection in green is the object representing the gate Porta del Leone, coded as GATE.02.

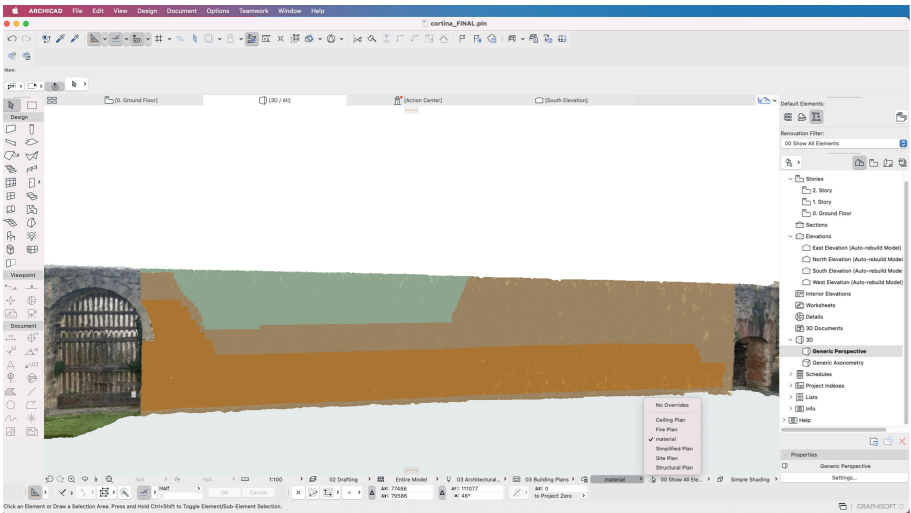


Fig. 6. Typed graphic view of the masonry classes set into the HBIM for the curtain wall CUR.04.

4 Conclusions

The procedural pipeline herein presented is designed for efficiently obtaining as-built 3D models that retain information on external dimensions, deformations and surface materials of city walls and, more generally, large architectural heritage. It allows for documenting and recording the characteristic of the building over a complete and sufficiently accurate model, which can be used to track and share data among heritage professionals. Textured 3D models can effectively support the diagnostic process by conveying data over time, enabling critical temporal evaluations and ensuring the revision of any piece of information by any actor involved in the conservation. As such, the proposed framework fully complies with the principles of HAM as it promotes knowledge-based decision making driven by comprehensive and updated data.

The proposal applies a scan-to-BIM approach that performs a fully automated 3D reconstruction of the scene from oriented images, thus limiting manual operations that are time-consuming and prone to errors. The case study herein presented demonstrates the proactive and efficient interaction between the 3D mesh file produced by Agisoft Metashape and other files post-processed by other software, such as McNeel Rhinoceros, Grasshopper and Graphisoft Archicad. The workflow stands out for the speed of importing complex mesh elements in the Graphisoft Archicad BIM environment, as well as for the possibility of compiling HBIM information in the Grasshopper environment using familiar nodes system. To conclude, the procedural pipeline has the advantage of indicating a scan-to-BIM procedure that is fast, lean and easily modifiable and customizable. Besides, it ensures a rapid exchange of up-to-date information and the interoperability among different tools that are already employed by professionals in the fields.

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